TIME EVOLUTION OF LOW FREQUENCY PERIODICITIES IN COSMIC RAY INTENSITY

K. Kudela
IEP/SAS, Watsonova 47, SK-04353 Košice, Slovak Republic

J. Rybák
Astronomical Institute/SAS, SK-05960 Tatranská Lomnica, Slovak Republic

A. Antalová
IEP/SAS, Watsonova 47, SK-04353 Košice, Slovak Republic

M. Storini
IFSI/CNR - Area di Ricerca Roma-Tor Vergata, Via del Fosso del Cavaliere, 100 - 00133 Roma, Italy
Raggi Cosmici, c/o Dip. di Fisica, UNIRoma3, Via della Vasca Navale, 84 - 00146 Roma, Italy

2000/04/29

Abstract. The long time series of daily means of cosmic ray intensity observed by four neutron monitors at different cutoff rigidities (Calgary, Climax, Lomnický Štít and Huancayo/Haleakala) were analyzed by means of the wavelet transform method in the period range $\sim$60 to $\sim$1000 days. The contributions of the time evolution of three quasiperiodic cosmic ray signals ($\sim$150-d, $\sim$1.3-y and $\sim$1.7-y) to the global one are obtained. While the $\sim$1.7-y quasiperiodicity, the most remarkable one in the studied interval, is strongly contributing to the cosmic ray intensity profile of solar cycle 21 (particularly in 1982), the $\sim$1.3-y one, which is better correlated with the same periodicity of the interplanetary magnetic field strength, is present as a characteristic feature for the decreasing phases of the cycles 20 and 22. Transitions between these quasiperiodicities are seen in the wavelet power spectra plots. Obtained results give a support to the claimed difference in the solar activity evolution during odd and even solar activity cycles.

1. Introduction

Periodicities with a duration longer than the diurnal one, have been reported by many authors after the inspection of cosmic ray time series, particularly those obtained by neutron monitors (NMs), and related to periodicities driven by solar activity. In addition to the power spectrum density (PSD), derived by usual FT methods (Attolini et al., 1975; Xanthakis, Mavromichalaki, and Petropoulos, 1989; Kudela, Ananth, and Venkatesan, 1991, among others), other techniques have been used in the past for identification of the significant cosmic ray periodicities (see, for instance, MEM method by Valdes-Galicia, Perez-Enriquez, and Otaola, 1996). Contrary to conventional spectral analysis, the wavelet transforms are suitable for the description of non-stationary processes containing multi-scale features, singularity detection and analysis

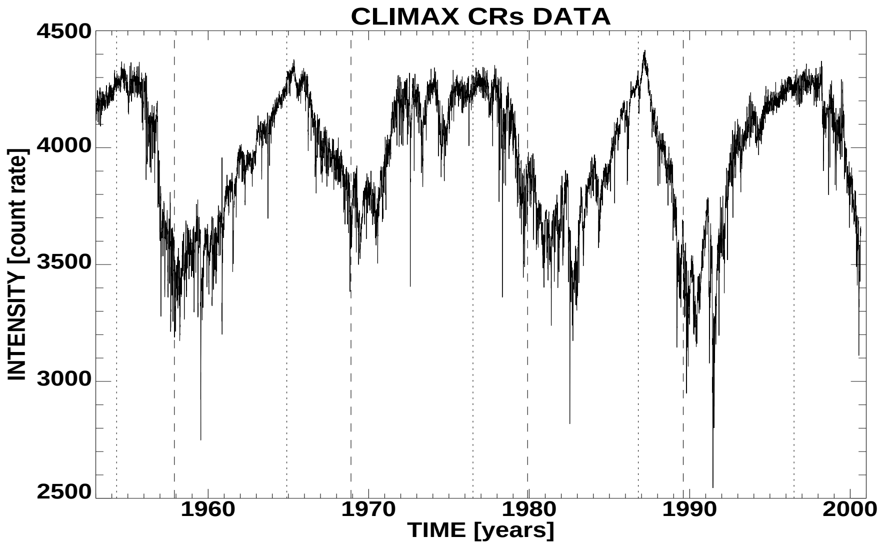

Figure 1. *Behaviour of the daily average count rate of CL NM after the GLE elimination. Dashed and dotted vertical lines depict solar activity maxima and minima, respectively.*

of transient phenomena. Hence, wavelet technique is used in many geophysical applications (see Kumar and Foufoula-Georgiou, 1997 and references therein). Nevertheless, this approach is not frequently used in cosmic ray studies; only few exceptions can be found (Astafyeva and Bazilevskaya, 1999; Kudela et al., 1999).

The aim of this paper is to present wavelet transform results from the time series of daily averages of the nucleonic intensity recorded by NMs at four different cut-off rigidities, over a period up to four solar cycles, and to describe the PSD temporal evolution at three periodicities, namely 150 – 160-d, ∼1.3-y and ∼1.7-y.

Section 2 briefly describes data used and methods of investigation and Section 3 summarizes main results. Our findings are discussed according with results obtained by other research teams in Section 4 and finally our conclusions are presented in Section 5.

2. Data and method of investigation

The counting rate of four NM-data sets have been examined, namely the daily means at stations with the effective cutoff rigidities (R_e) and covering the following time intervals: Calgary (CA: $R_e = 1.07$ GV, 1969 – 2000), Climax (CL: $R_e = 3.02$ GV, 1951 – 2000) shown in Fig.1, Lomnický Štít (LS: $R_e = 3.95$ GV, 1982 – 2000) and Huancayo/Haleakala (H/H: $R_e = 13$ GV, 1953 – 2000).

For the whole time interval the usual FT was used for deducing the power spectrum density (PSD). PSD was calculated applying the FFT procedure as $n/2 \times (a_i^2 + b_i^2)$, for $i = 1,2,...,(n-1)/2$, where a_i and b_i are cosine and sine transforms of the time series $x(t_i), i = 1,...,n$ (Box and Jenkins, 1976).

For checking the temporal evolution of the contribution of the different periodicities to the signal, the method of the continuous wavelet transform (WT) was used. This method is suitable for analysis of time series containing a non-stationary power at many different frequencies as its functions - wavelets - are localized in both time and frequency (e.g., Daubechies, 1990, Kumar and Foufoula-Georgiou, 1997, Torrence and Compo, 1998). The Morlet wavelet, a plane sine wave with an amplitude windowed in time by a Gaussian function, has been selected to search for variability at different frequencies over the whole length of the time series. This wavelet can be prescribed as the function $\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2}$, where η is an non-dimensional time parameter. The non-dimensional frequency ω_0 has been set to 6 fixing the length of all wavelets according to their scale s. The continuous wavelet transform of a discrete time series $x(t_i)$ can be defined (Torrence and Compo, 1998) as convolution of the data series with the wavelet $\psi(\eta)$ as $W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^*[(n'-n)\delta t/s]$, where ψ^* denotes the complex conjugative of the wavelet ψ and δt=1 day. Varying the scale s and translating along the time parameter η a picture of varying (if existing) amplitude for different scales can be determined over the whole time interval of the data series. The wavelet power spectrum $|W_n(s)|^2$ was calculated using the WT computational algorithm of Torrence and Compo (1998) to visualize the time-frequency behaviour of the data series power. The convenient set of scales $s_j = s_0 \times 2^{j.\delta j}$ ($j = 1,...,J$), where s_0=16 is the smallest computed scale and J=336 specifies the largest one, was used for the scale range $32 - 1024$ days with the scale resolution δj fixed to 48 scales per octave giving the scale resolution changing from 0.71 to 87.8 days. Due to the applied WT algorithm the wavelet power spectra are suppressed within the coins of incidence indicated in our plots by cross-hatched regions. Significance levels of the derived wavelet power spectrum has been derived using the null hypothesis according to Torrence and Compo (1998) assuming that the time series has a mean power spectrum. The global wavelet spectrum $\overline{W}^2(s) = \sum_{n=0}^{N-1} |W_n(s)|^2/N$ was used as an estimate of the mean power spectrum against which significance of the local wavelet power spectrum features were tested. The 95 % confidence level, used in this study, implies that 5 % of the wavelet power should be above this level for each scale.

To examine the existence of periodicities longer than 27 days, the normalized variation method, introduced by Stamper et al. (1999), was used. This method assigns the new time series of normalized variations $x'(t)$ from the

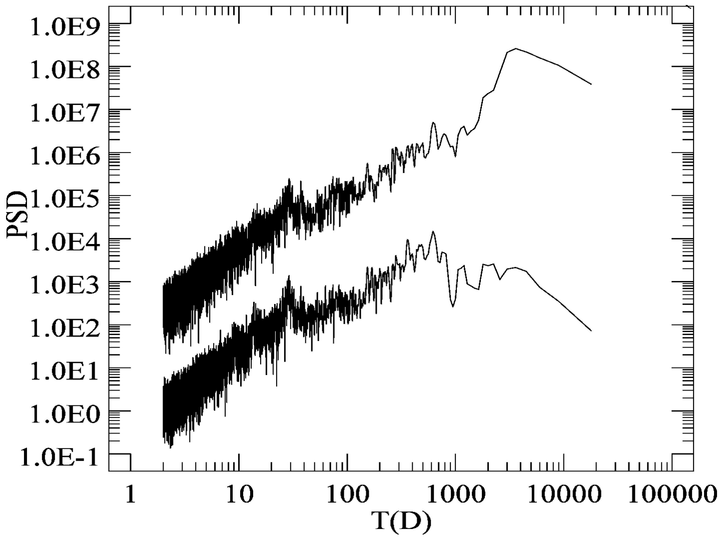

Figure 2. *Periodogram of the daily average count rate of CL NM after the GLE elimination. The upper curve is PSD (in relative units) of the original time series, the lower curve corresponds to 0.02×PSD of the filtered time series. The best fit for PSD of the original data is $f^{-1.72}$. The period T is given in days.*

original one, $x(t)$ as $x'(t) = (x(t) - X(t,w))/S(t,w)$, where X is the average and S is the standard deviation of x within the interval $(t-w, t+w)$ and where w is equal to 300 days in this work. In the following this method is named as F filter.

3. Main results

The longest data set of CL NM with the eliminated GLE (Fig.1) was checked by the usual FT method. The CL power spectrum density as a function of the period T (being the frequency f=1/T), if fitted in the whole frequency range, shows a frequency power law behaviour accounted by the slope -1.72 ± 0.01 (see Fig.2). This is in agreement with previous findings (see Owens and Jokipii, 1974, Kudela, Ananth, and Venkatesan, 1991, and references therein). However, the slope is flatter in the interval $\sim 40-800$-d, with clear signatures of $\sim$27-d (with its slighter second harmonic) and $\sim$11-y periodicities. Between the $\sim$27-d and $\sim$11-y periodicities there is a more complicated structure with indications of weaker signals at $\sim$150-d and $\sim 600-700$-d.

The spectral shape of H/H NM data is similar to the one of CL, while the other two are slightly different; the spectral index has a little bit larger error but is consistent with the one of CL. There are two reasons for that: shorter time series are available for CA and LS NMs and, at lower rigidities (especially for CA NM), GLEs are contributing to the time series.

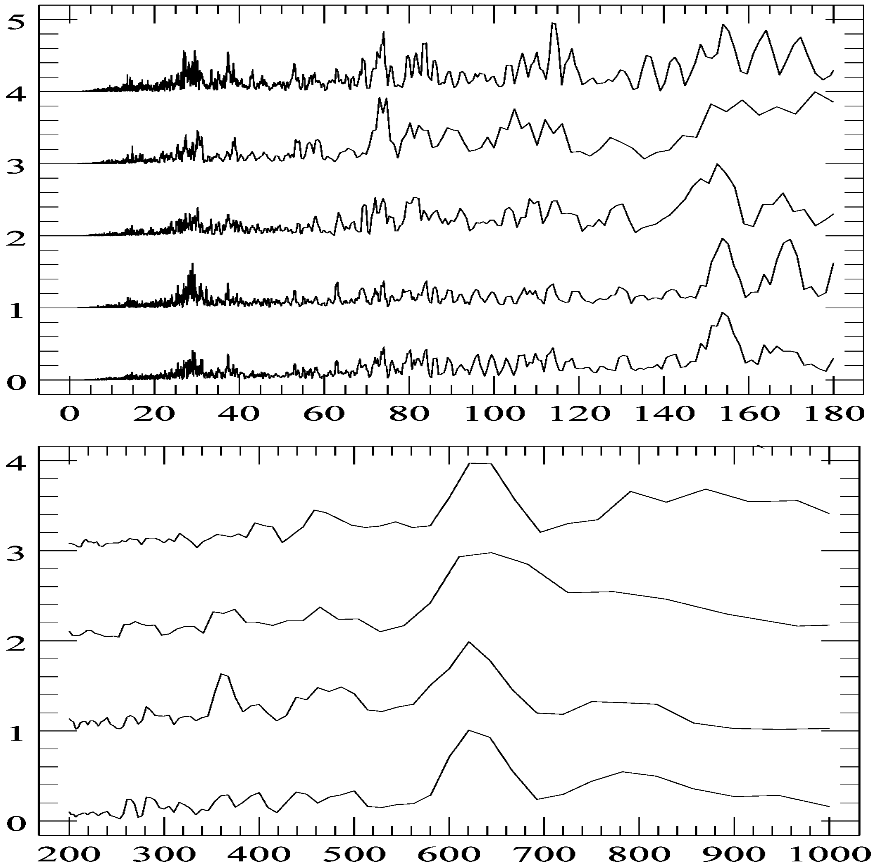

Figure 3. *Periodograms of the neutron monitor time series at two intervals of periodicities (T is in days). The upper panel gives the curves ordered from bottom to the top : Climax, Climax with F filter, Calgary, Lomnicky Stit and Huancayo/Haleakala. The lower panel gives from bottom to the top : Climax, Climax with F filter, Calgary and Huancayo/Haleakala, respectively. Maximum values of PSD in the respective intervals are adjusted to unity and shifted by 1 with respect to the previous profile.*

The effect of the applied F filter is to enhance the amplitudes of the periodicities if they persist as a slight signal in the original data. The difference between the PSDs of the original and filtered CL NM data can be seen in Fig.2. It can be checked also in Fig.3 comparing the first and second curves from the bottom. The periodicity centered at ∼154-d is present together with another one at ∼170-d in CL data, which was also reported by Joshi (1999). At higher rigidities there is a more complicated structure in the range 140 – 170-d and probably the effect of shorter time series (LS) is influencing this structure. On the other hand, stations more sensitive to higher energies like H/H and LS are showing a signature of the power increase at 70 – 75-d, which is less pronounced at CL and CA. At longer periodicities there is a clear peak at ∼620-d for CL NM (well seen also at CA and H/H), while the yearly variation, observed also in the near-Earth solar wind speed (Zieger and Mursula, 1998), and the possible 1.3-y periodicity are better discernable when the F filter is applied. A slight signature suggesting an increase in the range 440 – 500-d is seen too, also appearing at the H/H PDS profile.

The temporal evolution of the cosmic ray periodicities was analyzed by the continuous wavelet transform in the period range between 64 and 1024 days on daily basis. The WPS of CL and H/H normalized variations (Fig.4) clearly outline that the periodicities mentioned in Fig.2 and Fig.3 are not persistent with the same amplitude during the whole interval studied.

Focusing on the mentioned target periodicities, the upper panel of Fig.5 shows the comparison of the NM intensity WPS temporal profiles at ∼150-d at two different cutoff rigidities. The WPS temporal profiles for periodicities ∼1.3-y and ∼1.7-y are shown in the middle and lower panels. Figure 5 displays also the WPS temporal profiles of the daily averages of IMF strength (|B|), available from IMP satellites.[1]

It should be mentioned that the temporal profiles of WPS at ∼1.7-y, when original data are used (i.e. not filtered), indicate a signature of the changing power ratio at the two observed WPS peaks around 1982 (A-peak) and around 1991 (B-peak) with the cutoff rigidity R_e (Kudela et al., 2001). This ratio (A/B) is changing from 1/0.6 for Calgary NM (R_e∼1 GV) and 1/0.8 for Climax (∼3 GV), to 1/1.1 for Lomnický Štít (∼4 GV) and down to 1/1.55 for Huancayo/Haleakala (∼13 GV). Such tendency is not observed in the other two quasiperiodicities (∼150-d, ∼1.3-y). However, such kind of dependence is lost also at ∼1.7-y when the filter F is applied. To solve the question whether really the WPS temporal evolution of cosmic ray quasiperiodicities is depending on the primary particle energy or not, a similar type of analysis should be performed on muon data time series (sensitive to the particle energies higher than in case of the neutron monitors). A review on muon observations was recently done by Duldig (2000).

4. Discussion

The shortest quasiperiodicity checked here on NM data (∼150-d; Fig.5 upper panel) was found earlier in the IMF strength and in the solar wind speed at 1 AU (Cane, Richardson, and von Rosenvinge, 1998). Consistently with their results the IMF power average in 1978-1982 was found larger than in 1968-1972 for ∼150-d periodicity. Figure 4 indicates that this quasiperiodicity in cosmic rays is not stable and it ranges from 140 days to more than 200 days, appearing usually just after the solar maxima.

[1] IMP satellites IMF data are available at `http://nssdc.gsfc.nasa.gov/omniweb`

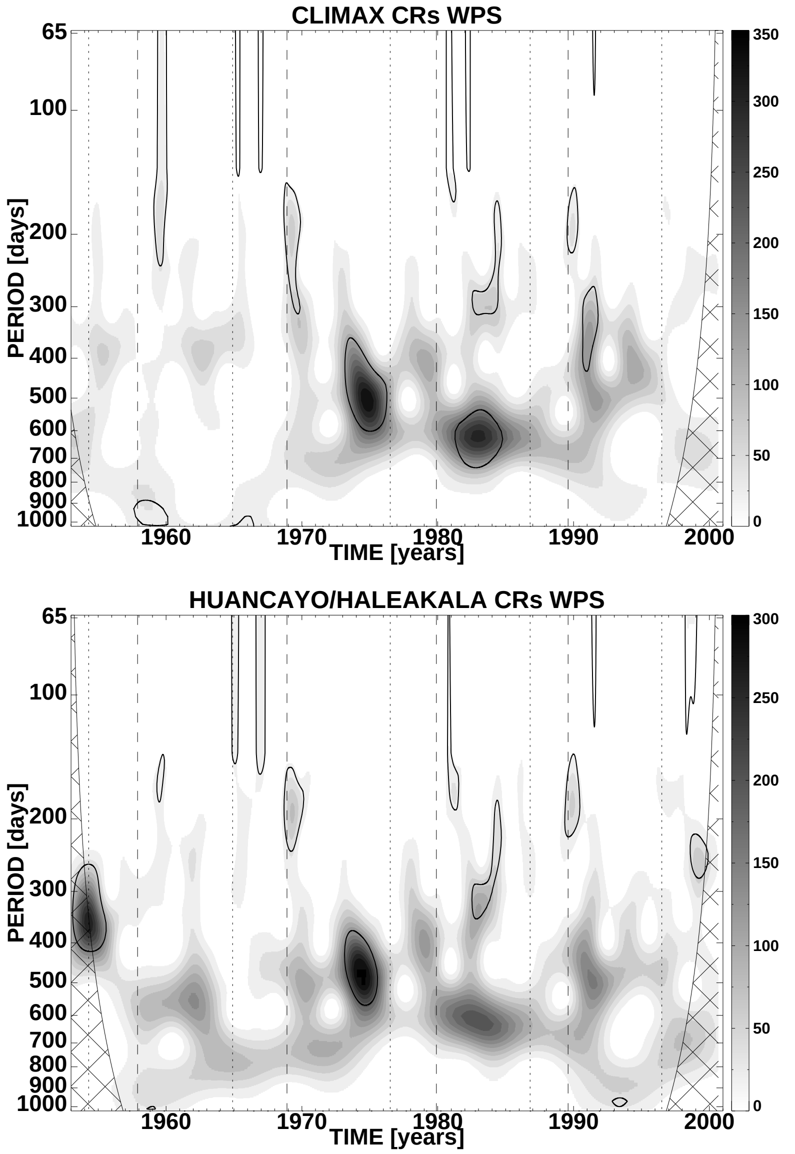

Figure 4. *WPS of Climax (top) and Huancayo/Haleakala (bottom) normalized variations (F filter was applied) obtained by the wavelet transform. Displayed wavelet power spectrum $|W_n(s)|^2$ values are multiplied by 0.01 and 0.1 respectively to plot the results in similar scales. Missing cosmic ray data were obtained by linear approximation from two neighbour values. The contours correspond to the 95% significant level. The coin of incidence is marked by the cross-hatched regions. Dashed and dotted vertical lines depict solar activity maxima and minima, respectively.*

Recently, significant variations with the ∼151-d periodicity of the ∼27 MeV anomalous cosmic rays were reported for the time interval 1998-1999 on Voyager-1 at a helioradius ∼73 AU by Hill, Hamilton and Krimigis (2001). These quasiperiodic variations may have a possible connection to the ∼154-d periodicity found in several solar indexes (e.g. Lean and Brueckner, 1989, Antalová, 1999 and references therein), in the IMF strength and other phenomena, but they were not observed in cosmic rays at ∼57 AU by Voyager-2.

The comparison of the middle and lower panels of Fig.5 reveals that, for the examined ranges of periodicities, both cosmic ray data sets have a similar power evolution. Looking at the three panels we may assert that the three selected periodicities contribute differently to the 'global cosmic ray signal' in time. For the cycle 21 the power at 1.3-y has smaller values if compared to the neighbour cycles. The largest value of power for this periodicity is observed at both cosmic ray stations (CL and H/H) during the decreasing phase of cycle 20 (1974 year). This strong contribution to the NM intensity signal is seen also in Fig.5 (upper panel), reported earlier by Valdes-Galicia, Perez-Enriquez, and Otaola (1996). It should be mentioned that for the period 1972-1976 (when the power at ∼1.3-y has the largest contribution to both signals: cosmic rays and IMF strength) Hundhausen et al. (1980) reported an enhanced correlation between cosmic ray intensity and the area of the polar coronal holes. On the other hand, the periodicity at 1.7-y is more importantly contributing to cosmic ray intensity during the cycle 21, if compared to the neighbours. The IMF strength at the Earth's orbit is showing better correspondence to cosmic ray behaviour at 1.3-y than that at 1.7-y. A 1.3-y periodicity is also present in the post-1986 data of solar wind speed (Richardson et al., 1994; Gazis, Richardson, and Paularena, 1995), in the North-South component of IMF, as well as in the Ap index time series (Paularena, Szabo, and Richardson, 1995). Recently, Mursula and Zieger (2000) studied this periodicity in the solar wind speed from 1964 onward and in the Kp index from 1932 onward. They showed this variation has a character of quasiperiodicity occurring during the even solar cycles, what is in good agreement with our results, for the last three solar cycles. However they found a new, somewhat longer periodicity (period of 1.5 – 1.7-y) during odd cycles. This ∼1.7-y periodicity was found in cosmic rays by Valdes-Galicia, Perez-Enriquez, and Otaola (1996). It was also examined in connection to the large scale photospheric motions (Valdes-Galicia and Mendoza, 1998) and identified in the occurrence of the sudden storm commencements (Mendoza et al., 1999). Earlier, this periodicity was reported for the coronal hole areas in the cycle 21 (McIntosh, Thompson, and Willock, 1992).

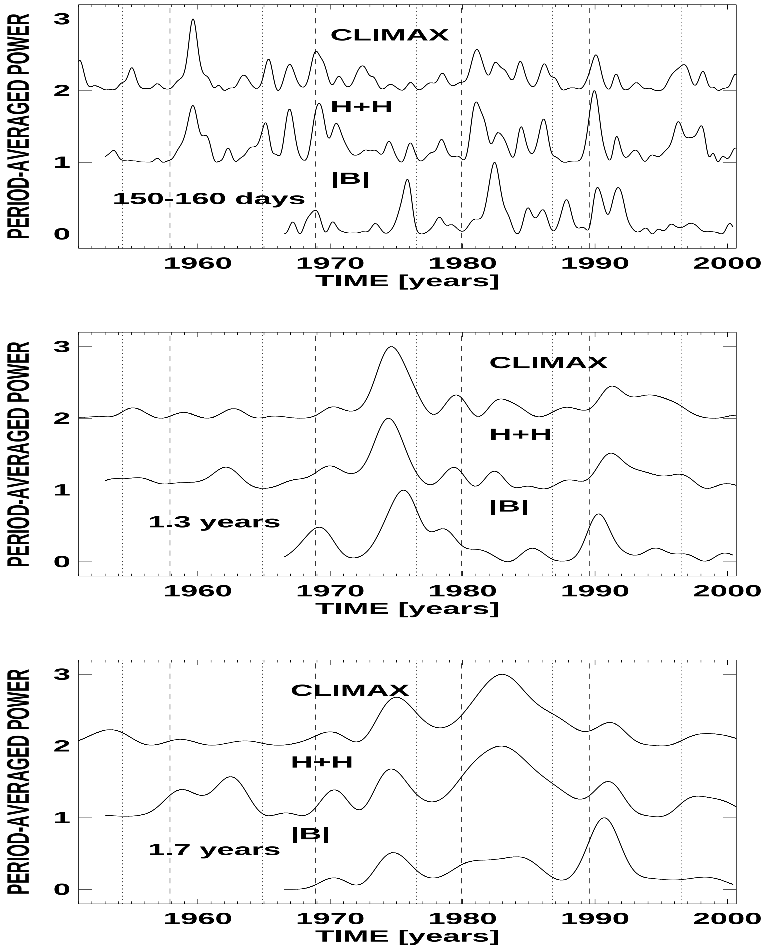

Figure 5. The averaged wavelet power spectra (i.e. $|W_n(s)|^2$ average over the limited period intervals) of two cosmic ray stations NM intensity (filtered data of Climax and Huancayo/Haleakala) and the IMF strength $|B|$. The upper panel is for ∼150-d period (interval 150.6-157.3 days), the middle one is for ∼1.3-y period (464.5-485.0 day interval), and the lowest panel for ∼1.7-y period (602.3-629.0 day interval). The values of H/H and CL power spectra were shifted by 1 and 2, respectively. Dashed and dotted vertical lines depict solar activity maxima and minima, respectively.

5. Conclusions

Investigation of low frequency periodicities in cosmic ray intensity, as recorded by four neutron monitor stations, was performed including their time evolution. The integral PSD of Climax NM data for the period 1951 – 2000, gave a power law behaviour in frequency with the exponent -1.72±0.01 in agreement with previous findings. However the wavelet results (Fig.4) indicate, instead, that there are no stable periodicities in cosmic ray intensity (in the sense of 'solar clock') in the whole range between $\sim$60 days to $\sim$1000 days examined here.

The quasiperiodicity which is seen clearly in the integral power spectra over past 47-49 years, is that of $\sim$1.7-y. It is observed similarly at two stations with different energies of primaries. For the last three cycles, in agreement with Valdes-Galicia and Mendoza (1998), its contribution is stronger during the post maximum years of the odd cycles (here clearly seen in the cycle 21). After the magnetic field reversal of the Sun the cosmic rays penetrate through the current sheet into the heliosphere if compared to the even cycle when their predominant drift via polar latitudes is suggested (e.g. Kóta and Jokipii, 1983, and Jokipii, 1998). Since the solar modulation is governed by the solar wind structures with the frozen in IMF, similarities between the cosmic ray behaviour and the time evolution of solar wind structures are expected. Our results (Fig.4) showed that, while on NM data the more dominant 'quasiperiodicity' with the center $\sim$1.7-y is seen in the odd cycle 21 (1981-1984), the enhanced (more dominant) contribution to the cosmic ray signal from the $\sim$1.3-y 'quasiperiodicity' is observed in the cycles before and after it (namely cycles 20 and 22). If alternating periodicities are a systematic feature of the consecutive cycles, it implies the relevance of the identified differences between even and odd solar activity cycles (Storini et al., 1995; Storini and Sýkora, 1995, Storini, 1997a,b, Bazilevskaya et al., 2000). In fact, this alternation could support differences in the space-time evolution of coronal holes (and hence in the active region locations) during even and odd cycles (e.g. Mursula and Zieger (2000) remarks from solar wind studies). However, more work is needed on the subject because it is not straightforward to relate cosmic ray variability directly to the solar periodicities, having in mind the different particle access from the interstellar medium into the inner heliosphere during periods with different polarity of the solar magnetic field.

Finally, to clarify the causal relations between solar modulation effects and cosmic ray flux on long-term basis, it should be useful to investigate the temporal variability of high energy particles near the Earth (muon time series), as well as available sets of cosmic ray records at larger distance simultaneously, together with the solar wind and IMF data sets at different points within the heliosphere using the same methods. One method to be applied should be that of the wavelet transform used here for the neutron monitor time series.

Acknowledgements

This work was supported by the Slovak grant agency (VEGA grants 2/1147/21 & 2/7229/20) and the IFSI/CNR-IEP/SAS cooperation via PNRA/MURST.

Thanks are due to the University of Chicago, National Science Foundation Grant ATM-9912341 and H. Graumann (University of Calgary) for NM data. C. Torrence and G. Compo are acknowledged for making available their wavelet computing code[2] and V. N. Obridko for suggesting the use of the F filter.

References

Antalová, A.: 1999, in *Magnetic Fields and Solar Processes*, ed. A.Wilson, Proceedings of the 9th European Meeting on Solar Physics, ESA SP-448, 743.

Astafyeva, N.M. and Bazilevskaya, G. A.: 1999, *Phys. & Chem. of the Earth (C)* **25**, 129.

Attolini, M. R., Cecchini, S., Guidi, I., and Galli, M.: 1975, *Planet. Space Sci.* **23**, 1603.

Bazilevskaya, G. A., Krainev, M. B., Makhmutov, V. S., Flückiger, E. O., Sladkova, A. I., and Storini, M.: 2000, *Solar Phys.* **197**, 157.

Box, G. E. P. and Jenkins, G. M.: 1976, *Time Series Analysis: Forecasting and Control*, Holden Day, San Francisco.

Cane, H. V., Richardson, I. G., and von Rosenvinge, T. T.: 1998, *J. Geophys. Res.* **25**, 4437.

Daubechies, I.: 1990, *IEEE Transactions on Information Theory* **36**, 961.

Duldig, M. L.: 2000, *Space Sci. Rev.* **93**, 207.

Gazis, P. R., Richardson, J. D., and Paularena, K. I.: 1995, *Geophys. Res. Lett.* **22**, 1165.

Hill, M. E., Hamilton, D. C., and Krimigis, S. M.: 2001, *J. Geophys. Res.* **106**, 8315.

Hundhausen, A. J., Sime, D. J., Hansen, R. Y., and Hansen, S. F.: 1980, *Science* **207**, 761.

Jokipii, J. R.: 1998, in *From the Sun: Auroras, Magnetic storms, Solar flares, Cosmic rays*, eds. S.T. Suess, B.T. Tsurutani, American Geophysical Union, Washington, 123.

Joshi, A.: 1999, *Solar Phys.* **185**, 397.

Kóta, J. and Jokipii, J. R.: 1983, *Astrophys. J.* **265**, 573.

Kudela, K., Ananth, A. G., and Venkatesan, D.: 1991, *J. Geophys. Res.* **96**, 15,871.

Kudela, K., Yasue, S.-I., Munakata, K., and Bobik, P.: 1999, *Proc. 26th ICRC*, Salt Lake City, 7,163.

Kudela, K., Antalová A., Rybák, J., and Storini, M.: 2001, contribution to the ISCS 2001 Workshop, Longmont, CO, June 13-16, 2001.

Kumar, P. and Foufoula-Georgiou, E.: 1997, *Rev. of Geophys.* **235**, 385.

Lean, J. L. and Brueckner, G. E.: 1989, *Astrophys. J.* **337**, 568.

McIntosh, P. S., Thompson, R. J., and Willock, E. C.: 1992, *Nature* **360**, 322.

Mendoza, B., Lara, A., Maravilla, D., and Valdes-Galicia, J. F.: 1999, *Solar Phys.* **185**, 405.

Mursula, K. and Zieger, B.: 2000, *Adv. Space Res.* **25(9)**, 1939.

Owens, A. J. and Jokipii, J. R.: 1974, *J. Geophys. Res.* **79**, 907.

Paularena, K. I., Szabo, A., and Richardson, J. D. L.: 1995, *J. Geophys. Res.* **22**, 3001.

Richardson, J. D., Paularena, K. I., Belcher, J .W., and Lazarus, A. J.: 1994, *Geophys. Res. Lett.* **21**, 1559.

Stamper, R., Lockwood, M., Wild, M. N., and Clark, T. D. G.: 1999, *J. Geophys. Res.* **104**, 28,325.

Storini, M.: 1997a, *Report CNR/IFSI-97-1*, Frascati, Italy.

Storini, M.: 1997b, *Il Nuovo Cimento* **20C**, 871.

Storini, M. and Sýkora, J.: 1995, *Contr. Astron. Obs. Skalnaté Pleso* **25**, 90.

[2] The wavelet computing code is available at `http://paos.colorado.edu/research/wavelets`

Storini, M., Borello-Filisetti, O., Mussino, V., Parisi, M., Sýkora, J.: 1995, *Solar Phys.* **157**, 375.
Torrence, C. and Compo, G. P.: 1998, *Bull. Amer. Meteorol. Society* **79**, 61.
Valdes-Galicia, J. F., Perez-Enriquez, R., and Otaola, J. A.: 1996, *Solar Phys.* **167**, 409.
Valdes-Galicia, J. F. and Mendoza, B.: 1998, *Solar Phys.* **178**, 183.
Xanthakis, J., Mavromichalaki, H., and Petropoulos, B.: 1989, *Solar Phys.* **122**, 345.
Zieger, B. and Mursula, K.: 1998, *Geophys. Res. Lett.* **25**, 841.

Address for Offprints:
Karel Kudela
Department of Space Physics, Institute of Experimental Physics, Slovak Academy of Sciences
Watsonova 47, SK-04353 Košice, Slovak Republic
(kkudela@kosice.upjs.sk)